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**Population viability analysis for the South Newfoundland Atlantic Salmon
(*Salmo salar*) designatable unit**

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Analyses of recent status and trends as well as a population viability analysis (PVA) were conducted for the South Newfoundland Atlantic Salmon designatable unit (DU 4). Trend analyses were conducted for each South Coast Salmon Fishing Area (SFAs 9-12), four currently monitored rivers (Conne River, Little River, Northeast Brook and Rocky River) and the composite index of these rivers. For individual rivers, only Conne River and Little River in SFA 11 had statistically significant declines in salmon abundance since 1996 (56% and 71% respectively). Population viability analyses were conducted using eight average marine survival values (2% to 9%) and four fishing mortality rates: no angling, catch-and-release only angling, half of current angling and current angling (includes retention and catch-and-release mortality). All possible combinations of marine survival values and fishing mortality rates were assessed to estimate the probability of meeting or exceeding each of three population abundance levels in the next 15 years: current population size, conservation requirement/recovery target and the pre-decline mean. Under current conditions (1996-2010) the probability of DU 4 Atlantic Salmon meeting or exceeding the conservation requirement/recovery target in the next 15 years was 27%. Removing angling mortality increased this probability to 50%. As expected, marine survival has a very strong influence on the potential recovery of DU 4 salmon. An increase in average marine survival from 4% to 5% over the next 15 years improved the probability of achieving the conservation requirement/recovery target from 27% to 66% under current angling rates. This probability reaches 85% with no angling. Given that estimated catch-and-release fishing mortality was relatively low, population projections were generally similar to no angling. The probability of DU 4 Atlantic Salmon remaining at their current population size over the next 15 years was 48% under current angling rates and 72% under no angling. These proportions increase to 87% and 96%, respectively, if average marine survival increased from 4% to 5% over the next 15 years. In general, the probability that DU 4 Atlantic Salmon abundance will increase was greatly improved with higher marine survival rates and management measures to reduce angling mortality.

Analyse de la viabilité de la population de saumon atlantique (*Salmo salar*) de l'unité désignable du sud de Terre-Neuve

RÉSUMÉ

Des analyses de tendances et d'états récents, ainsi qu'une analyse de viabilité de population ont été réalisées pour l'unité désignable (UD 4) du saumon de l'Atlantique du sud de Terre-Neuve. Des analyses de tendances ont été effectuées dans chacune des zones de pêche du saumon de la côte Sud (ZPS 9 à 12) dans quatre rivières qui font l'objet d'une surveillance (la rivière Conne, la rivière Little, le ruisseau Northeast et la rivière Rocky) de l'indice composite de ces rivières. En ce qui concerne chacun de ces cours d'eau, seules les rivières Conne et Little dans la ZPS 11 ont enregistré des déclin importants de l'abondance du saumon depuis 1996 (56 % et 71 % respectivement). Des analyses de viabilité de population ont été réalisées en utilisant huit valeurs de survie marine moyennes (2 % à 9 %) et quatre taux de mortalité par pêche : sans pêche à la ligne, pêche à la ligne avec remise à l'eau, la moitié de la pêche à la ligne actuelle et la pêche à la ligne actuelle (comprend la conservation et la mortalité par pêche avec remise à l'eau). Toutes les combinaisons possibles de valeurs de survie marine et de taux de mortalité par pêche ont été évaluées pour évaluer la probabilité d'atteindre ou de dépasser chacun des trois niveaux suivants liés à l'abondance de la population au cours des 15 prochaines années : taille actuelle de la population, exigence en matière de conservation et cible de rétablissement et moyenne précédant le déclin. Dans les conditions actuelles (1996-2010), la probabilité que le saumon de l'Atlantique de l'UD 4 atteigne et dépasse les exigences de conservation et les cibles de rétablissement au cours des 15 prochaines années s'élève à 27 %. Le fait de retirer la mortalité par pêche à la ligne hausse cette probabilité à 50 %. Comme on s'y attendait, la survie marine influe énormément sur le potentiel de rétablissement du saumon de l'UD 4. Une augmentation de la survie marine moyenne qui passerait de 4 % à 5 % au cours des 15 prochaines années, ferait passer de 27 % à 66 % la probabilité d'atteindre les exigences de conservation et les cibles de rétablissement, et ce, aux taux actuels de pêche à la ligne. Sans pêche à la ligne, cette probabilité atteindrait un taux de 85 %. Étant donné que le taux estimé de mortalité par pêche avec remise à l'eau est relativement bas, les prévisions de population sont généralement semblables aux prévisions sans pêche à la ligne. La probabilité que la population du saumon de l'Atlantique de l'UD 4 demeure à sa taille actuelle au cours des 15 prochaines années est de 48 % (aux taux actuels de pêche à la ligne) et de 72 % (sans pêche à la ligne). Ces proportions passent à 87 % et à 96 % respectivement, si la survie marine moyenne passe de 4 % à 5 % au cours des 15 prochaines années. En général, la probabilité d'une augmentation de l'abondance du saumon de l'Atlantique dans l'UD 4 a connu une grande amélioration, grâce aux taux de survie marine plus élevés et aux mesures de gestion réduisant la mortalité par pêche à la ligne.

INTRODUCTION

In November 2010, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) designated the South Newfoundland Atlantic Salmon (*Salmo salar* L., 1758) designatable unit (DU 4) as threatened due to significant declines in the abundance of both small salmon (< 63 cm fork length) (37%) and large salmon ($\geq$ 63 cm) (26%) from 1994 to 2007 (COSEWIC 2010). The COSEWIC report noted that there has been a significant historical decline in salmon beyond the last three generations (i.e. prior to 1994) and stated that extending the time series back one additional year would have produced decline rates of 52% and 50% for small and large salmon respectively. Decline rates equal to, or in excess of 50% are considered within the Endangered status category.

A recovery potential assessment (RPA) was conducted by Fisheries and Oceans Canada (DFO) Science to provide information and scientific advice required to meet various requirements of the *Species at Risk Act* (SARA). The advice in the RPA may be used to inform both scientific and socio-economic elements of the listing decision, in the development of a recovery strategy and action plan, and to support decision-making with regards to the issuance of permits, agreements and related conditions, as per relevant sections of SARA. A Science Advisory Report (SAR), Recovery Potential Assessment (RPA) for the South Newfoundland Atlantic Salmon DU4 has been published and contains an update of the status, threats to its survival and recovery, and the feasibility of its recovery (DFO 2013).

The purpose of this document was to provide a brief overview of the status of South Newfoundland salmon populations and details of the population viability analysis (PVA) conducted to assess recovery potential. Population viability analysis is a modelling technique developed to predict the likelihood of populations in decline going extinct (Boyce 1992; Beissinger and McCullough 2002) and is a powerful tool for exploring the potential consequences of management actions intended to conserve populations (Reed et al. 2002). This approach has been used for Atlantic Salmon populations in the Gulf of Maine, Bay of Fundy and Québec (Legault 2005; Gibson et al. 2008; Palstra and Dionne 2011).

CURRENT/RECENT STATUS

The status of South Newfoundland Atlantic Salmon (DU 4) was assessed using monitoring facility data, recreational fishery data (1969-2010), and commercial catch data prior to the salmon moratorium in 1992 (1969-1992). The most recent estimate (2010) of adult abundance, after all fisheries have taken place (i.e. spawning escapement), for DU 4 was 22,404 salmon (range 15,262-29,546 salmon), with 20,744 (range 14,065-27,423) small salmon and 1,660 (range 1,197-2,123) large salmon. Abundance of DU 4 Atlantic Salmon declined by 42% for small salmon (fork length < 63 cm) and 48% for large salmon ($\geq$ 63 cm) during the previous three generations from 1996 to 2010 (DFO 2013).

The trend analyses conducted for DU 4 were also applied to each South Coast SFA (9-12) (Figs. 1a and 1b), the currently monitored rivers (Conne River, Little River, Northeast Brook and Rocky River) (Figs. 2a and 2b) and the composite index of these four rivers (Fig. 3). The composite index provides a standardized metric of relative changes in individual river abundance. Therefore, the unit for the composite index is not an absolute abundance but is related to a geometric mean of individual river abundances. Details of the methods used and a summary of the results were presented in the SAR (DFO 2013) (Table 1). For individual rivers, only Conne River and Little River in SFA 11 had statistically significant declines in salmon abundance since 1996 (56% and 71% respectively) (DFO 2013).

CONNE RIVER – A RETROSPECTIVE ANALYSIS

It has been suggested that the substantial decline of Atlantic Salmon in Conne River resulted from anomalously high abundances recorded when monitoring began in 1986. During the first five years that salmon abundance was monitored (1986–90) returns of small salmon averaged over 7200. Returns over the past 10 years (2002–11) have averaged around 2200 small salmon. To better understand whether the 1986 to 1990 returns were anomalously high a retrospective analysis was carried out to infer possible abundance of the Conne River population during the ten year period prior to 1986.

Procedures were similar to that used by the International Council for the Exploration of the Sea (ICES) to infer pre-fishery abundance of salmon in the North Atlantic (e.g. Reddin and Veinott 2010; ICES 2011; Chaput 2012). Estimates of angling exploitation rates were used to expand recreational catch data to provide information on total returns. At Conne River, exploitation rates for the period 1986 to 1990 were estimated from the reported angling catch and the total returns of salmon to the fish counting fence. Angling catch from 1986 to 1990 averaged 1401 small salmon (range: 767 to 2060). Total returns of small salmon averaged 7284 (range: 4968 to 10155) with a corresponding mean angling exploitation rate of 0.192 (range: 0.14–0.25). The above rates were then applied to the 1976–85 angling catch to estimate salmon returns. For the simulations, angling catch was assumed to vary by $\pm 25\%$ each year and randomly selected from a uniform distribution to reflect potential uncertainty in the reported catch data. Exploitation rates were also randomly selected from a uniform distribution within the range observed from the 1986 to 1990 data (0.14–0.25). Two thousand realizations were run.

Most scenarios suggested that returns to Conne River would have been much higher than that observed from 1986 to 1990 despite commercial salmon fisheries operating on the south coast at that time. One scenario, using the original base information, suggested median abundances averaging 11,000 small salmon. A second scenario, based on a higher range of angling exploitation rates (0.35–0.50) provided median abundances averaging 5500 small salmon. The latter exploitation rates, however, would be anomalously high based on information derived at Conne River and in comparison with most other rivers in Newfoundland where angling exploitation could be evaluated. A third scenario used similar exploitation rates derived from 1986 to 1990 (0.14–0.25), but reduced the angling catch by 40% as the reported catches themselves had produced anomalously high returns. This scenario suggested median abundances averaging 6700 small salmon, about 8% lower than that observed from 1986 to 1990. Other simulations were run in an attempt to produce abundances of salmon similar to that observed in recent years (2001–11; ~2000 to 2500 small salmon). To do so required using unusually high angling exploitation rates (0.35–0.50) coupled with catch data discounted by as much as 50%, neither of which was likely. Thus, the results of various simulations suggest that the high returns of salmon to Conne River during the first five years of monitoring (1986–90) were likely not anomalous and that the river has declined dramatically since the early 1990s (Fig. 4). This conclusion is also consistent with local and traditional ecological knowledge regarding historical salmon abundance in Conne River (personal communication Ross Hinks, Miawpukek First Nation).

DEVELOPMENT OF PVA MODEL

LIFE HISTORY PARAMETERS

The life-history model used to describe the population dynamics of DU 4 Atlantic Salmon included two stages: a density dependent freshwater stage based on adult - or egg - to smolt production and a density independent marine stage in which marine survival was directly related

to the number of returning small adult salmon (< 63 cm fork length) that are predominantly maiden one-sea-winter fish.

Freshwater Stage: Adult-to-smolt production

Spawner and smolt data (assigned back to egg year) were available from three currently monitored rivers in DU 4: Conne River (n = 20 years; 1986-2005), Rocky River (n = 19 years; 1987-2005) and Northeast Brook Trepassey (n = 22 years; 1984-2005). All returning adult salmon (small and large) were considered as spawners in a given year for stock-recruit relationships used to predict the number of smolts produced based on the number of adult spawners. All smolts were considered to have migrated at age 3 (mean modal smolt age) (Chaput et al. 2006). Beverton-Holt and Ricker stock-recruit curves were fit for all three rivers and extrapolated to DU 4 based on the relative amount of fluvial habitat units in each river and in DU 4 (Table 2).

Stock-Recruit Analyses

The Beverton-Holt model was defined as,

$$(1) S_{y+3} = \frac{\alpha N_y}{1 + \frac{\alpha N_y}{K}}$$

where S is the number of smolts produced by the number of spawners N in year y , α is the slope-at-origin of the stock-recruit curve and K is the asymptotic carrying capacity of the environment (maximum number of smolts produced, S_{max}).

Analyses were run on a per-fluvial habitat area basis and fit using lognormal errors.

Model fits to the data are depicted in Fig. 5. For individual rivers, estimates of K were significant ($p < 0.001$), while α -values were not significant due to large error associated with the parameter estimate (Table 2). However, the fit for all of DU 4 (both parameters $p < 0.001$) was better than that for over individual river models.

The Ricker model was defined as,

$$(2) S_{y+3} = \alpha N_y e^{-\beta N_y}$$

Where β is the rate which recruitment declines with increasing spawners N , $1/\beta$ is the number of spawners at which the maximum number of smolts are produced (S_{max}).

Both parameter estimates were significant for Ricker fits for each of the three rivers and for all of DU 4 ($p < 0.001$).

Autocorrelation of residuals in Beverton-Holt and Ricker models

To estimate the degree to which years may be correlated, the correlation of residual values between year y and year $y+1$ were estimated based on the residuals of model fits for both types of stock-recruit curves. Estimates differed among rivers, and were combined for the entire DU 4 by taking an average of the values obtained for the three rivers (Table 2).

Standard deviation in stock-recruit curves

The overall standard deviation of the model fits for stock-recruit curves (σ) were obtained from the analysis in R of the residual error in the stock-recruit curves. This term was used in the projection models to allow for reasonable variation in projected population sizes.

Random deviates were incorporated into the stock-recruit portion of the life-history model following Gibson et al. (2008) and Hilborn (2001). Gibson et al. (2008) described the equations as follows, for an instantaneous rate of mortality, $\bar{M}$ as:

$$(3) M_t^{fw} = \bar{M} \exp(w_t - \frac{\sigma^{fw^2}}{2})$$

where,

$$(4) w_t = w_{t-1}d^{fw} + w_t\sigma^{fw}$$

and,

$$(5) w_t \sim N(0,1)$$

where w is a set of normally distributed numbers with a mean of 0 and a standard deviation of 1 and d^{fw} is the temporal autocorrelation of the residuals of the stock-recruit relationship.

Marine Stage: Smolt-to-adult production

Marine mortality

Average marine mortality (m_{sea}) over the previous 15 years (1996-2010) was estimated at 96% (4% survival) for all of DU 4 using data from Conne River, Rocky River and Northeast Brook Trepassey (Table 3). The standard deviation of marine mortality (σ_{sea}) was determined over the same time period and was 2%. In addition, the autocorrelation of marine mortality ($m_{sea,d}$) was estimated from binomial regressions of marine mortality in each river (DFO 2013).

To account for year-to-year variation in marine mortality as well as autocorrelation between years, a vector of marine mortality incorporating variation and the autocorrelation between subsequent years was included in the projections for the 15 year time span.

$$(6) M_t^{sea} = m^{sea} + h_t$$

where,

$$(7) h_t = h_{t-1}d^{sea} + h_t\sigma_{sea}$$

and,

$$(8) h_t \sim U[-1,1]$$

where h_t is a set of uniformly distributed values ranging between -1 and 1 and d^{sea} is the temporal autocorrelation of marine mortality. This allowed for year-to-year variation in marine mortality of $\pm 2\%$ of the mean mortality specified in the model.

Fishing mortality

Two components of fishing mortality were incorporated into population projections: retention mortality and catch-and-release mortality. Both mortality estimates were based on retention and release values for the past 15 years (1996-2010). Only small salmon are retained, and catch-and-release mortality was determined for large and small salmon separately. Retention mortality values for small salmon were the average proportion of small salmon retained based on data from 1996-2010. Retention mortality (f^{retain}) over the past 15 years was 12% of the total small salmon population of DU 4.

Catch-and-release mortality was further subdivided into two parts for small ($f^{c.r.s.}$) and large ($f^{c.r.l.}$) salmon based on the average proportion of fish released from 1996-2010 for small and

large salmon, respectively. These estimates were based on a 10% mortality rate for all fish that are caught and released. Overall catch-and-release mortality based on all fish in DU 4 was 2% of total small salmon and 1% of total large salmon.

The number of smolts returning as salmon after one winter at sea was defined using a linear relationship that removed fish based on marine mortality and fishing mortality estimates. All salmon were assumed to mature and return as small salmon. The number of adults returning from sea for the first time (N_t^{1sw}) was calculated as:

$$(9) N_t^{1sw} = S_{t-1}(1 - (f^{retain} + f^{c.r.s}))(1 - M_t^{sea})$$

where S is the number of smolts determined from the stock-recruit relationship, M_t^{sea} is the mortality at sea, and f^{retain} and $f^{c.r.s}$ are retention and catch-and-release mortality, respectively.

Repeat spawners

For simplicity, large salmon were assumed to be repeat spawners. To estimate the proportion of repeat spawners in DU 4, the total number of large salmon in year y was divided by the number of small salmon in year $y-1$ from 1996-2010. The average proportion of large salmon from a given year was 16%, resulting in a mortality after first spawning (m^{spawn}) of 84%.

Given that large salmon are not subject to retention mortality, they were considered separately in the population projection model. Repeat spawning was allowed to occur only once. The number of large salmon contributing to the next generation in any given year was defined as:

$$(10) N_t^{repeat} = N_{t-1}^{1sw}(1 - m^{spawn})(1 - f^{c.r.l.})$$

The total number of spawners in a given year producing smolts was the sum of repeat spawning fish and maiden one-sea-winter fish (first time spawners).

Recovery Target

To satisfy COSEWIC's assessment criteria to declare that a species is *not threatened* the recovery target for South Newfoundland Atlantic Salmon DU 4 was considered to be the conservation spawner requirement (CSR) of 30,852 salmon (O'Connell et al. 1997; DFO 2013). The rationale for the use of the CSR as the recovery target was based on its use in the management of salmon populations in eastern Canada (CAFSAC 1991a, 1991b). Two other DU 4 Atlantic Salmon abundance levels were considered for comparison in the population projections; 1) No further decline of the current level of 22,404 salmon and 2) the pre-decline mean (1981-1995) of 42,792 salmon (DFO 2013).

Population Projections

Population abundance for DU 4 was projected for 15 years into the future from 2010 based on the two-stage life-history model parameters described in Table 4. The estimates included a 5-year time lag from adult-to-adult, to account for the three year freshwater stage, the one year marine stage and the time from adult return to egg hatching. The models were initiated with the most recent 5 years of data for large and small salmon (2006-10, inclusive) to complete the projected adult-to-adult life cycle.

To obtain overall population abundances, Beverton-Holt and Ricker estimates were transformed from a per fluvial habitat unit basis to an overall population size by multiplying K or dividing β by the total number of habitat units in DU 4.

Given that the Beverton-Holt and Ricker models resulted in good fits to the DU 4 data (Fig. 5), population abundance was projected using the combined data set from both models. Projection analyses were conducted using eight different average marine mortality values observed in

monitored rivers over the past 15 years (91% to 98% mortality, or 2% to 9% survival) which included a 2% deviation as described above.

Four different fishing scenarios were included in the projections to assess the potential for management measures to facilitate recovery: no angling, catch-and-release only angling, half of current angling and current angling (retention and catch-and-release). All possible combinations of marine mortality values and fishing scenarios were assessed. Each of these analyses was based on 1000 simulations.

For each marine mortality value and fishing scenario, the probability of meeting each of three population abundance levels was assessed: current population size (22,404 adults), conservation requirement/recovery target (30,852) and the pre-decline mean (42,792) (Table 5) (Figs. 6-13).

DISCUSSION

Under current conditions (1996-2010) the probability of DU 4 Atlantic Salmon meeting or exceeding the conservation requirement/recovery target in the next 15 years was 27%. Management measures that remove fishing mortality (i.e. no angling) increased this probability to 50%. As expected, marine survival has a very strong influence on the potential recovery of DU 4 salmon (Legault 2005, Gibson et al. 2008, Palstra and Dionne 2011). An increase in average marine survival from 4% to 5% over the next 15 years improved the probability of achieving the conservation requirement/recovery target from 27% to 66% under current angling mortality. This probability reaches 85% with no angling. Given that the estimated catch-and-release fishing mortality was relatively low (Reddin and Veinott 2010), population projections were generally similar to no angling.

The probability of DU 4 Atlantic Salmon remaining at their current population size over the next 15 years was 48% under current angling rates and 72% under no angling. These proportions increase to 87% and 96%, respectively, if average marine survival increased from 4% to 5% over the next 15 years. In general, under all fishing mortality rates, maintaining current abundance or achieving the conservation requirement/recovery target over the next 15 years would most likely occur if marine survival improves to 6% or 7%. Achieving the pre-decline mean would likely require a marine survival rate of 8%.

The life-history model used to project population size may be subject to a number of potential limitations. The model was based on data from only three of 104 watersheds in DU 4 which, due to substantial scaling, makes estimates of population parameters uncertain (McCarthy et al. 2001, Reed et al. 2002). Populations differ in the way they adapt to environmental influences which results in variable population parameters over a geographic range. However, given the available data, the Beverton-Holt and Ricker density-dependent model fits to the data based on stock-recruit analysis on a per fluvial habitat unit basis for all of DU 4 were significant. Another limitation of the model was that the estimates for temporal autocorrelation in mortality were based on a short time period (15 years) to reflect current population conditions over the previous three generations. Accurate estimation of autocorrelation often requires time series of 100 years or more (Lande et al. 2003).

Despite these uncertainties, the PVA suggested that it was unlikely that DU 4 Atlantic Salmon would recover under current conditions in the next 15 years. The probability of recovery would be greatly improved if marine survival increased and management measures were introduced to reduce fishing mortality.

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Table 1. Results from abundance trend analyses (percent change and P-value) of Atlantic Salmon escapement/spawners during the past three generations (1996-2010) for DU 4, SFAs 9-12, Conne River, Northeast Brook, Rocky River and Little River. Results from the DU 4 COSEWIC Status Report trend analyses (1995-2007) are included for comparison. Statistically significant trends are bolded.

Assessed Area	Percent Change (P-value)		
	Small Salmon	Large Salmon	Total Salmon
DU 4 (SFAs 9-12) COSEWIC Status Report 1995-2007	-37.3 (0.063)	-26.2 (0.293)	-36.0 (0.071)
DU 4 (SFAs 9-12)	-41.5 (0.009)	-48.3 (0.012)	-42.4 (0.006)
SFA 9	-33.1 (0.202)	-42.5 (0.152)	-34.4 (0.184)
SFA 10	-29.5 (0.147)	-41.3 (0.102)	-31.2 (0.126)
SFA 11	-52.1 (0.002)	-56.1 (0.002)	-52.6 (0.001)
SFA 12	-31.1 (0.277)	-36.8 (0.195)	-31.9 (0.253)
South Coast Index	-31.9 (0.091)	-85.6 (<0.0001)	-40.1 (0.024)
Conne River (SFA 11)	-55.5 (0.002)	-64.8 (0.001)	-56.1 (0.001)
Little River* (SFA 11)	-66.1 (0.032)	-95.3 (<0.0001)	-71.0 (0.009)
Northeast Brook (SFA 9)	-11.0 (0.620)	-80.6 (<0.0001)	-22.8 (0.271)
Rocky River (SFA 9)	+78.8 (0.055)	-53.0 (0.123)	+54.4 (0.084)

* Total returns of salmon minus known removals other than those for brood stock were used for Little River. Brood stock removals and fry stocking occurred to 2001.

Table 2. Model fits (Standard Error) for Beverton-Holt and Ricker models for Conne River, Rocky River, and Northeast Brook Trepassey. Autocorrelation of the model residuals and the standard deviation of model fits are also provided.

Beverton-Holt Model	Fluvial Habitat Units (100m ²)	α (S.E.)	K (S.E.)	Autocorrelation	σ
Conne River	13,180	346.67 (526.69)	5.57 (0.69)	0.12	0.21
Rocky River	10,823	218.23 (236.03)	1.16 (0.24)	0.35	0.32
Northeast Brook	556	64.00 (44.98)	3.58 (0.84)	0.01	0.24
ALL DU 4	293,794	39.54 (4.62)	6.89 (1.08)	0.16 ¹	0.38
Ricker Model	Fluvial Habitat Units (100m ²)	α (S.E.)	β (S.E.)	Autocorrelation	σ
Conne River	13,180	53.64 (6.11)	3.38 (0.39)	0.04	0.23
Rocky River	10,823	83.00 (20.15)	29.06 (7.00)	0.33	0.30
Northeast Brook	556	28.97 (5.21)	3.45 (0.95)	0.002	0.25
ALL DU 4	293,794	33.57 (2.78)	2.67 (0.41)	0.11 ¹	0.39

¹ All DU 4 autocorrelation values were calculated from an average of autocorrelation values for individual rivers.

Table 3. Average marine mortality, standard deviation and range of marine mortality for Atlantic Salmon in each of Conne River, Rocky River and Northeast Brook Trepassey. Autocorrelation of marine mortality was estimated for each river and the average of these values was used for DU 4 population projections.

River	Average Mortality	S.D.	Range (min-max)	Autocorrelation
Conne River	96%	2%	92%–96%	0.10
Rocky River	95%	2%	91%–97%	0.07
Northeast Brook	96%	1%	93%–98%	0.28
ALL DU 4	96%	2%	91%–98%	0.15

Table 4. Parameters used in DU 4 Atlantic Salmon population projections. Constant parameter values for the two models are reported as Beverton-Holt / Ricker.

Parameter	Definition	Type	Value
α	Slope-at-origin of the Beverton-Holt and Ricker model	Constant	38 / 39
β	Inverse spawner population size at which the maximum number of smolts are produced in the Ricker model	Constant	2.76
K	Carrying capacity per habitat unit	Constant	6.89
$density$	Number of habitat units	Constant	293,784
σ^{fw}	Standard deviation of freshwater production	Constant	0.38 / 0.39
d^{fw}	Serial autocorrelation of stock-recruit residuals	Constant	0.16 / 0.11
m^{sea}	Sea mortality	Variable	0.91 – 0.98
σ_{sea}	Variability in sea mortality	Constant	2×10^{-2}
$m_{sea,d}$	Autocorrelation of sea mortality	Constant	0.1
$p.mat_{1sw}$	Probability of maturation after one year at sea	Constant	1
$spawn_{max}$	Maximum repeat spawnings per fish	Constant	1
σ_{sea}	Standard deviation of marine mortality	Constant	0.02
d_{sea}	Serial autocorrelation of marine mortality	Constant	0.15
n_{years}	Number of years to project	Constant	15
$n_{simulations}$	Number of simulations	Constant	1000
f_{retain}	Retention fishery mortality	Variable	0.06, 0.12
$f_{r,s}$	Catch-and-release mortality of small salmon	Constant	0.02
$f_{r,l}$	Catch-and-release mortality of large salmon	Constant	0.01

Table 5. Probabilities of meeting or exceeding three DU 4 Atlantic Salmon population abundances at average marine survival rates from 2% to 9% (91% to 98% mortality) and four angling scenarios.

	Marine Survival							
	2%	3%	4%	5%	6%	7%	8%	9%
Current Abundance								
No Angling	0.04	0.32	0.72	0.96	1.00	1.00	1.00	1.00
Catch-and-Release	0.04	0.26	0.69	0.93	0.99	1.00	1.00	1.00
Half of Current Angling	0.03	0.20	0.58	0.91	0.99	1.00	1.00	1.00
Current Angling	0.01	0.12	0.48	0.87	0.97	1.00	1.00	1.00
Conservation Requirement/Recovery Target								
No Angling	0.02	0.15	0.50	0.85	0.98	1.00	1.00	1.00
Catch-and-Release	0.01	0.12	0.47	0.81	0.96	1.00	1.00	1.00
Half of Current Angling	0.01	0.09	0.37	0.76	0.93	0.98	1.00	1.00
Current Angling	0.00	0.05	0.27	0.66	0.89	0.98	1.00	1.00
Pre-decline mean								
No Angling	0.00	0.06	0.27	0.62	0.86	0.97	0.99	1.00
Catch-and-Release	0.00	0.04	0.25	0.60	0.80	0.96	0.99	1.00
Half of Current Angling	0.00	0.03	0.16	0.50	0.76	0.93	0.98	1.00
Current Angling	0.00	0.01	0.12	0.38	0.70	0.87	0.97	0.99

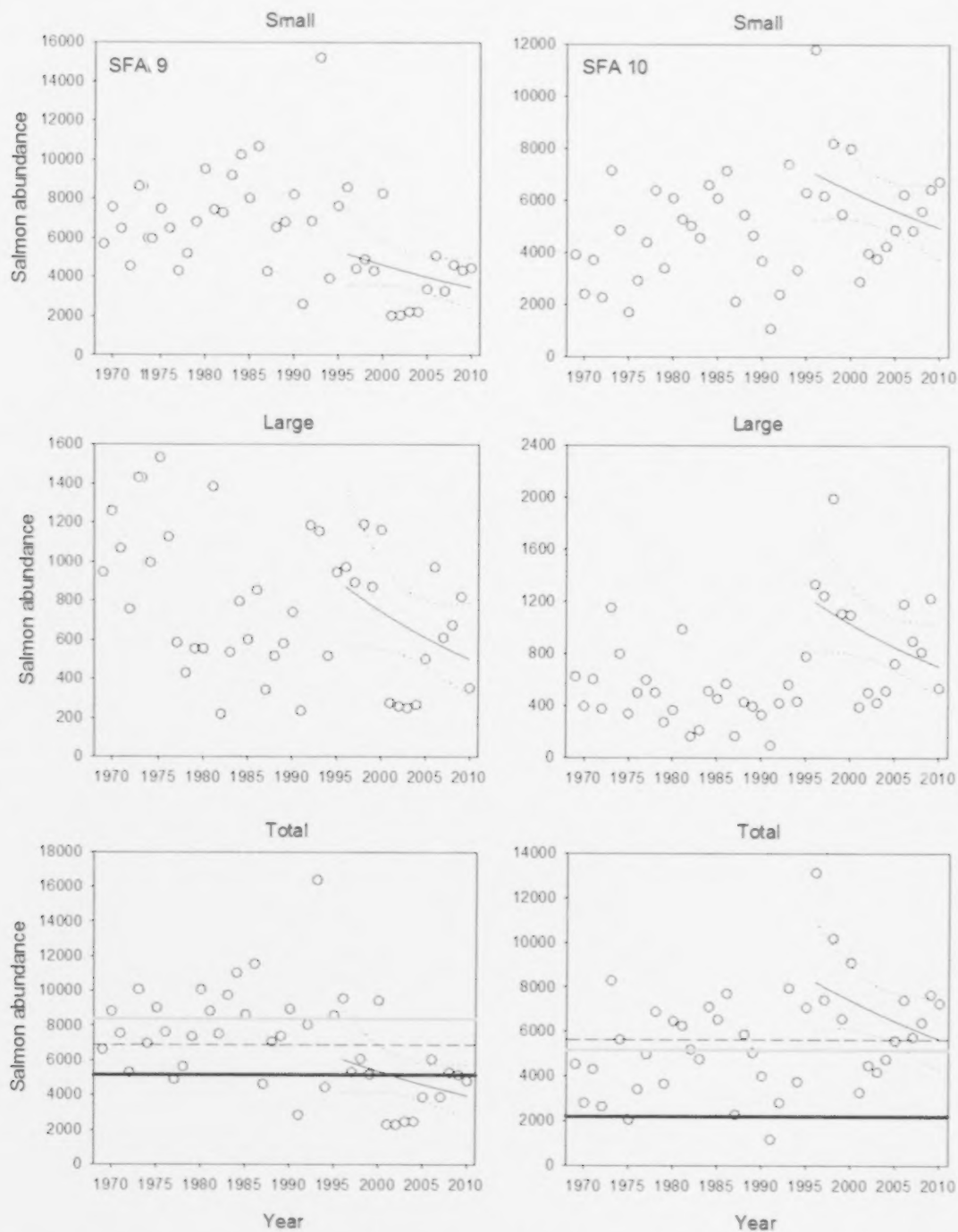


Figure 1a. Atlantic Salmon abundance (mean) for SFA 9 (left panels) and SFA 10 (right panels) (small: top panel; large: middle panel; total: bottom panel) (1969-2010). Superimposed is the general linear model (± 2 SE prediction intervals) used to determine trends in abundance over the past three generations (1996-2010). The three horizontal lines represent the estimated conservation spawner requirement from O'Connell et al. 1997 (solid black line), long-term mean (dashed black line), and three generations prior to the current trend analyses (1981-95) (solid grey line).

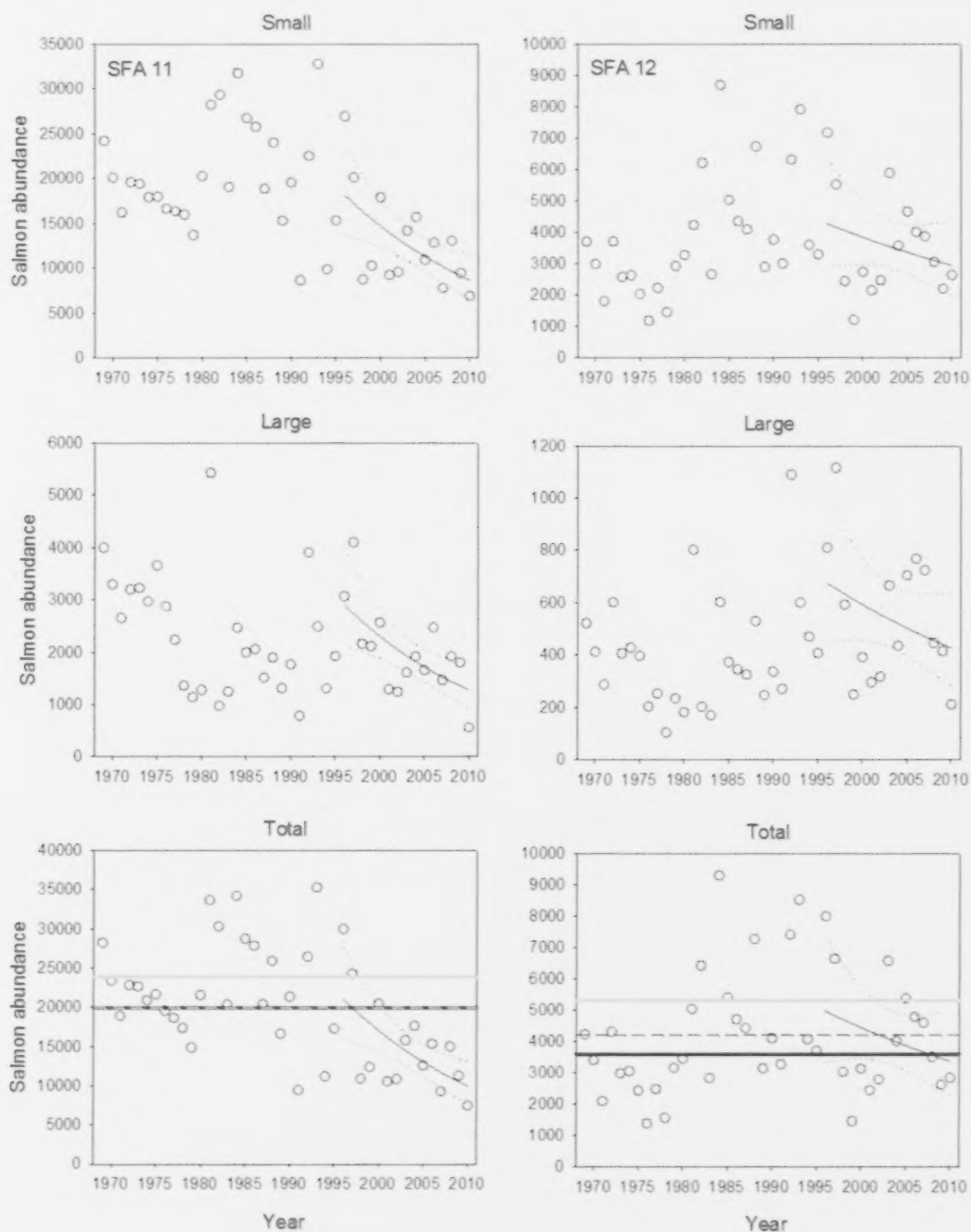


Figure 1b. Atlantic Salmon abundance (mean) for SFA 11 (left panels) and SFA 12 (right panels) (small: top panel; large: middle panel; total: bottom panel) (1969-2010). Superimposed is the general linear model ($\pm 2SE$ prediction intervals) used to determine trends in abundance over the past three generations (1996-2010). The three horizontal lines represent the estimated conservation spawner requirement from O'Connell et al. 1997 (solid black line), long-term mean (dashed black line), and three generations prior to the current trend analyses (1981-95) (solid grey line).

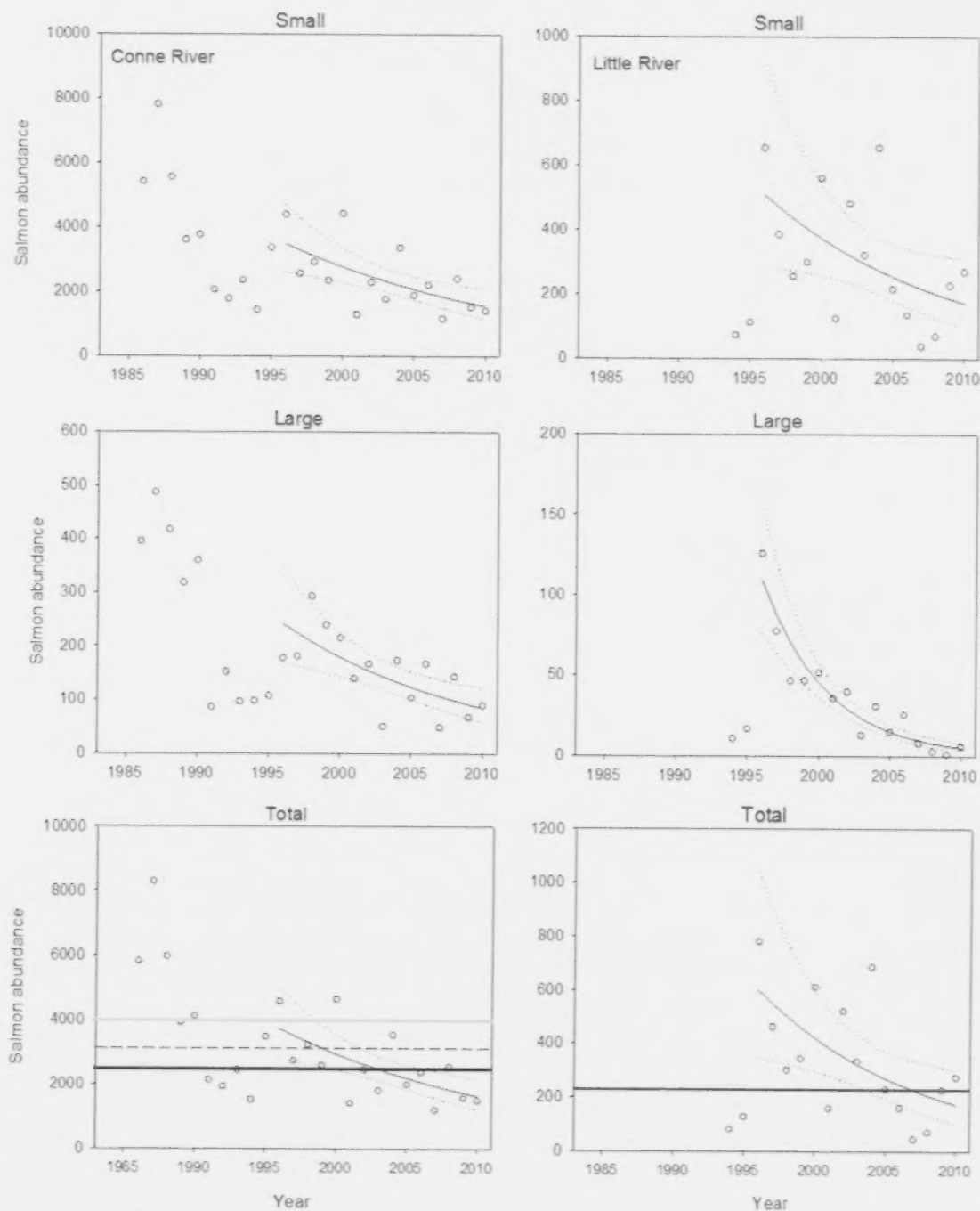


Figure 2a. Atlantic Salmon abundance (mean) for Conne River (1986-2010) (left panels) and Little River (1994-2010) (right panels). Superimposed is the general linear model ($\pm 2SE$ prediction intervals) used to determine trends in abundance over the past three generations (1996-2010). The three horizontal lines represent the estimated conservation spawner requirement (solid black line), long-term mean (dashed black line), and three generations prior to the current trend analyses (1981-95) (solid grey line).

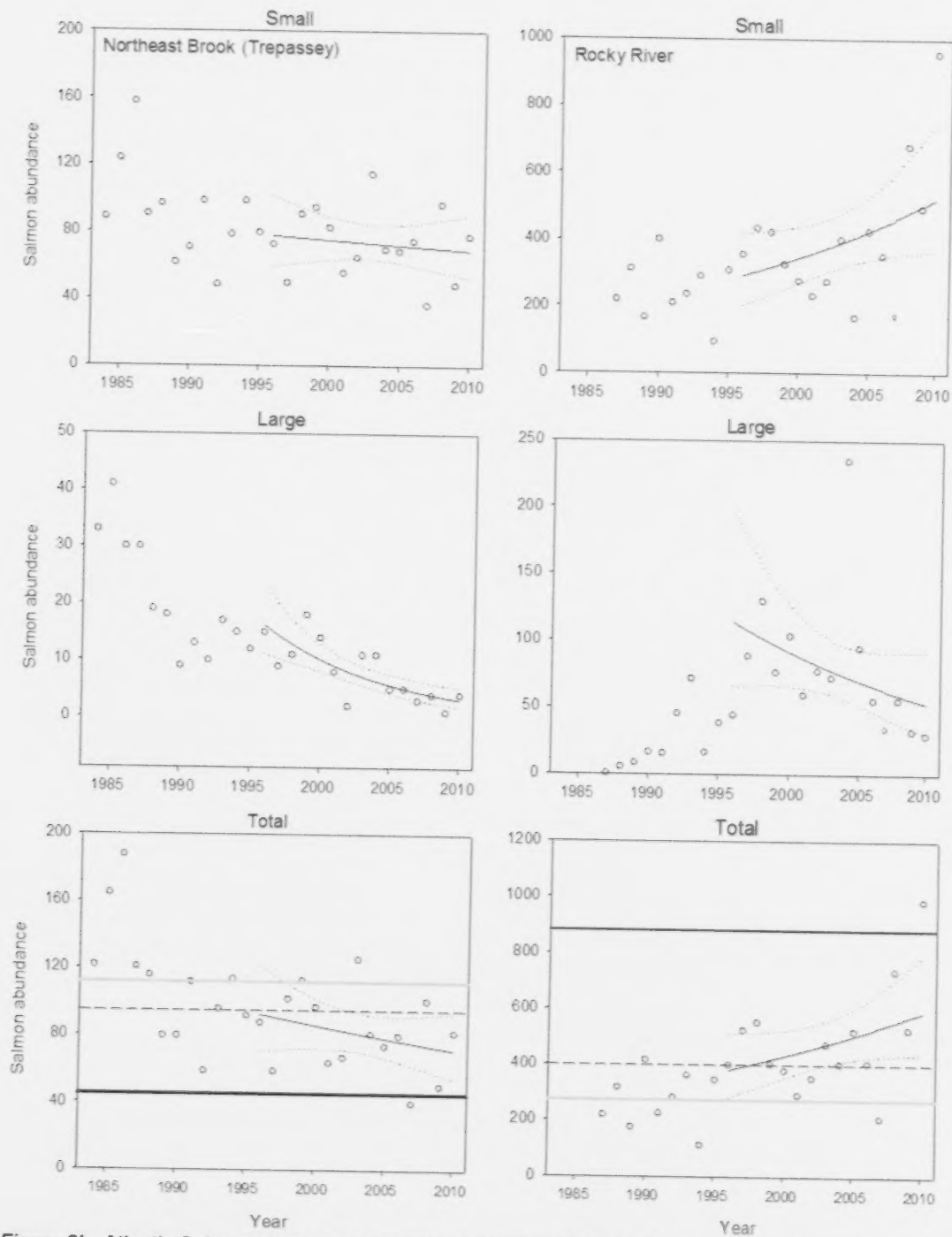


Figure 2b. Atlantic Salmon abundance (mean) for Northeast Brook (Trepassey) (1984-2010) (left panels) and Rocky River (1987-2010) (right panels). Superimposed is the general linear model ($\pm 2SE$ prediction intervals) used to determine trends in abundance over the past three generations (1996-2010). The three horizontal lines represent the estimated conservation spawner requirement (solid black line), long-term mean (dashed black line), and three generations prior to the current trend analyses (1981-95) (solid grey line).

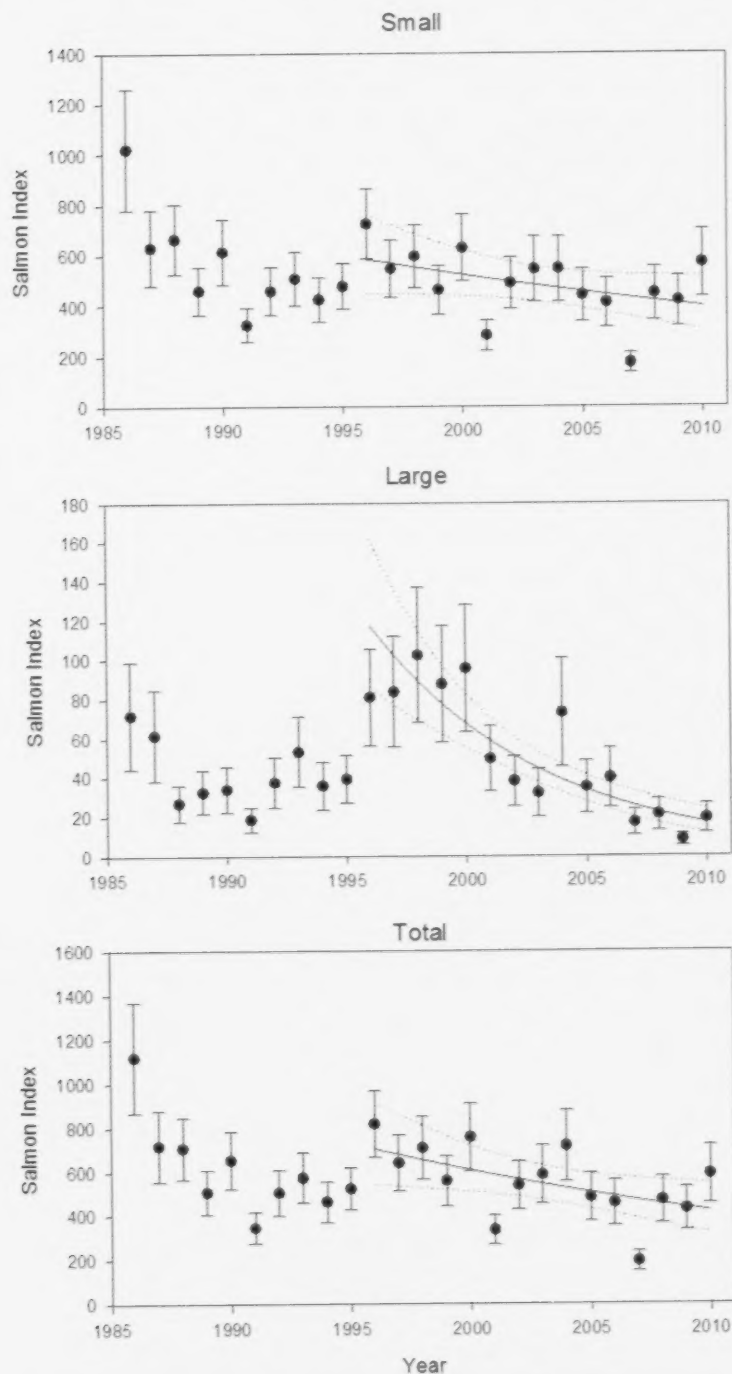


Figure 3. Trends in the Atlantic Salmon abundance index ($\pm 1SE$) from the four rivers currently assessed on the south coast of Newfoundland (SFA 9 and 11) from 1986 to 2010. Superimposed is the general linear model ($\pm 2SE$ prediction intervals) used to determine trends in abundance over the past three generations (1996-2010). (Note: The y-axis represents an abundance index that is related to the geographic mean of individual river abundances and not absolute abundance).

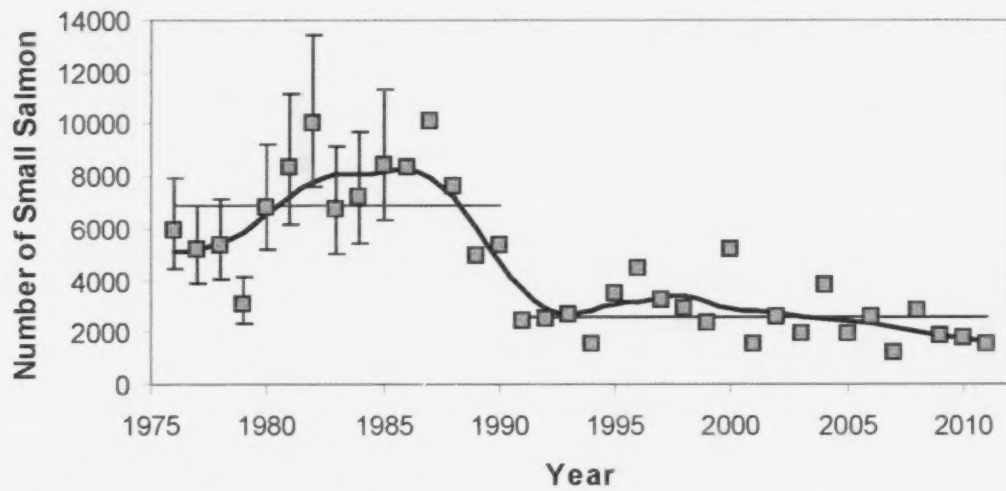


Figure 4. Simulated Atlantic Salmon returns to Conne River, 1976-85, with observed returns for 1986-2011. Vertical bars for 1976-85 represent the 10th and 90th percentiles about the median while the solid horizontal lines relate to the 1976-90 and 1991-2011 mean values.

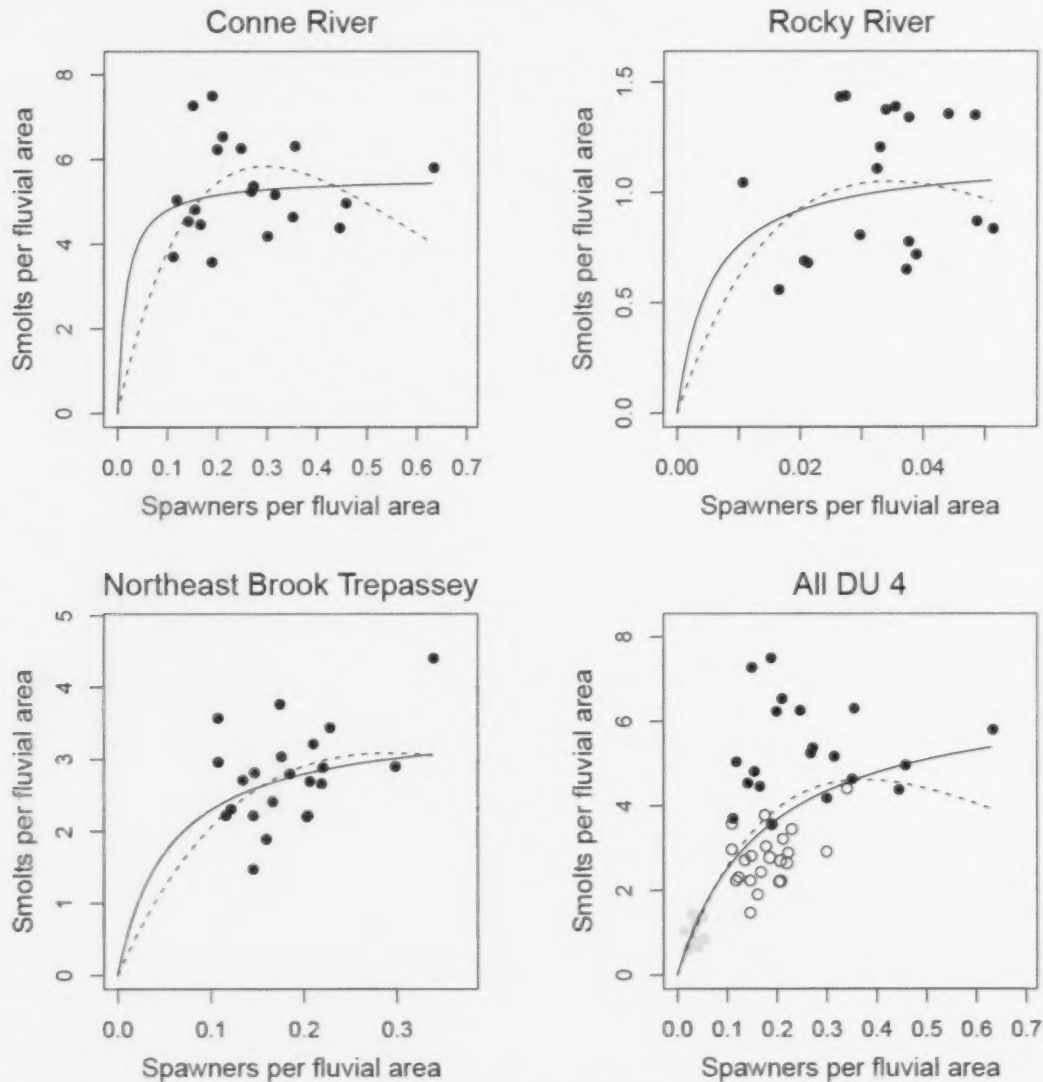


Figure 5. Number of Atlantic Salmon smolts produced versus number of spawners per fluvial habitat unit (100m²) for Conne River, Rocky River, Northeast Brook Trepassey and all of DU4 (black fill: Conne River; grey fill: Rocky River; white fill: Northeast Brook Trepassey). Lines represent Beverton-Holt (solid lines) and Ricker (dashed lines) model fits to the data.

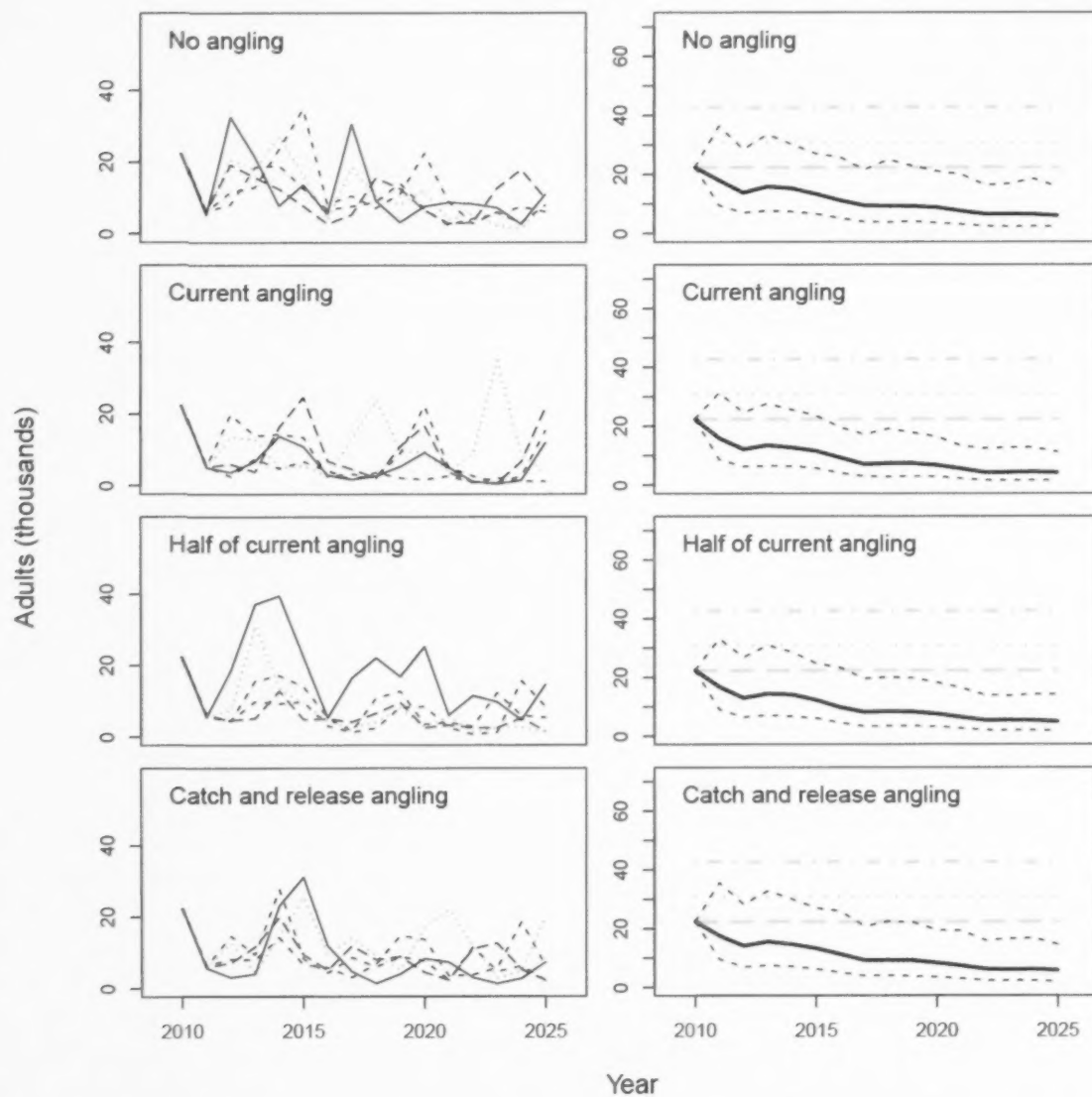


Figure 6. Population projections for DU 4 Atlantic Salmon using the combined Beverton-Holt and Ricker models for freshwater production and an average marine survival of 2%. Plots on the left represent 5 randomly selected projections from a total of 1000 simulations. Plots on the right show median values from 1000 simulations per year. Dashed black lines represent 10th and 90th percentiles of the data. Grey lines represent population abundances levels for current abundance (dashed line), conservation requirement/recovery target (dotted line) and pre-decline mean (dash-dot-dash line).

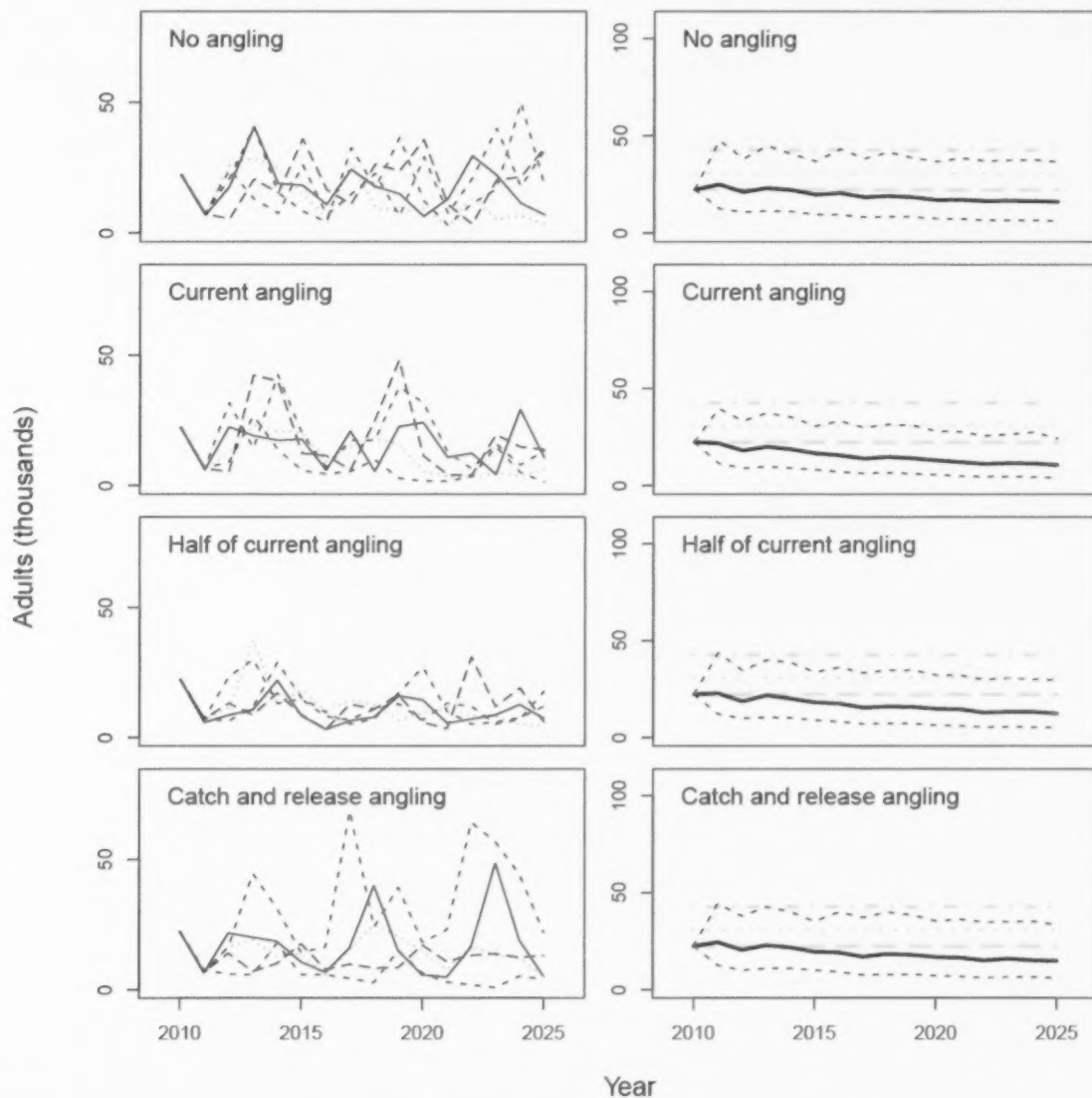


Figure 7. Population projections for DU 4 Atlantic Salmon using the combined Beverton-Holt and Ricker models for freshwater production and an average marine survival of 3%. Plots on the left represent 5 randomly selected projections from a total of 1000 simulations. Plots on the right show median values from 1000 simulations per year. Dashed black lines represent 10th and 90th percentiles of the data. Grey lines represent population abundances levels for current abundance (dashed line), conservation requirement/recovery target (dotted line) and pre-decline mean (dash-dot-dash line).

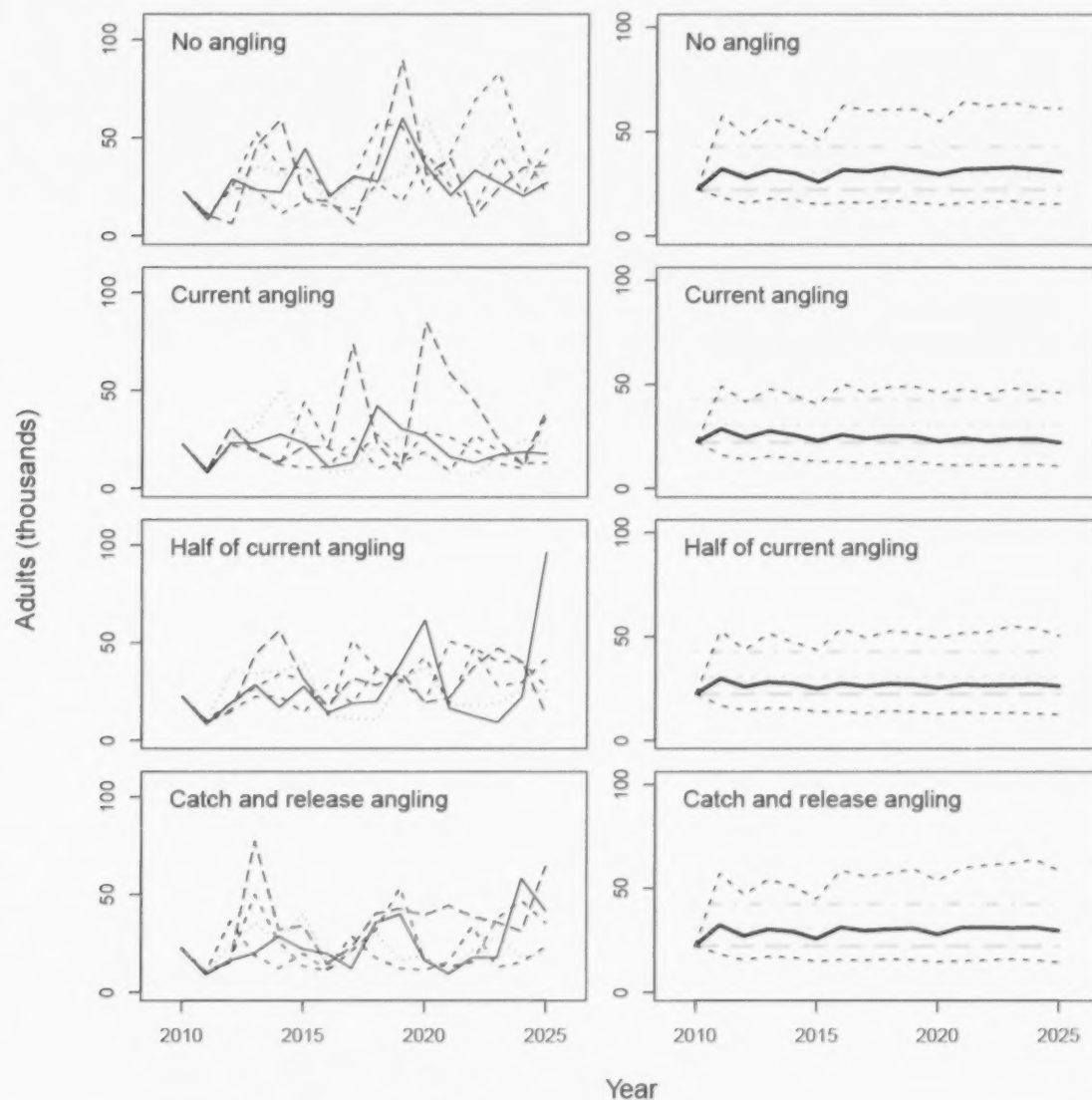


Figure 8. Population projections for DU 4 Atlantic Salmon using the combined Beverton-Holt and Ricker models for freshwater production and an average marine survival of 4%. Plots on the left represent 5 randomly selected projections from a total of 1000 simulations. Plots on the right show median values from 1000 simulations per year. Dashed black lines represent 10th and 90th percentiles of the data. Grey lines represent population abundances levels for current abundance (dashed line), conservation requirement/recovery target (dotted line) and pre-decline mean (dash-dot-dash line).

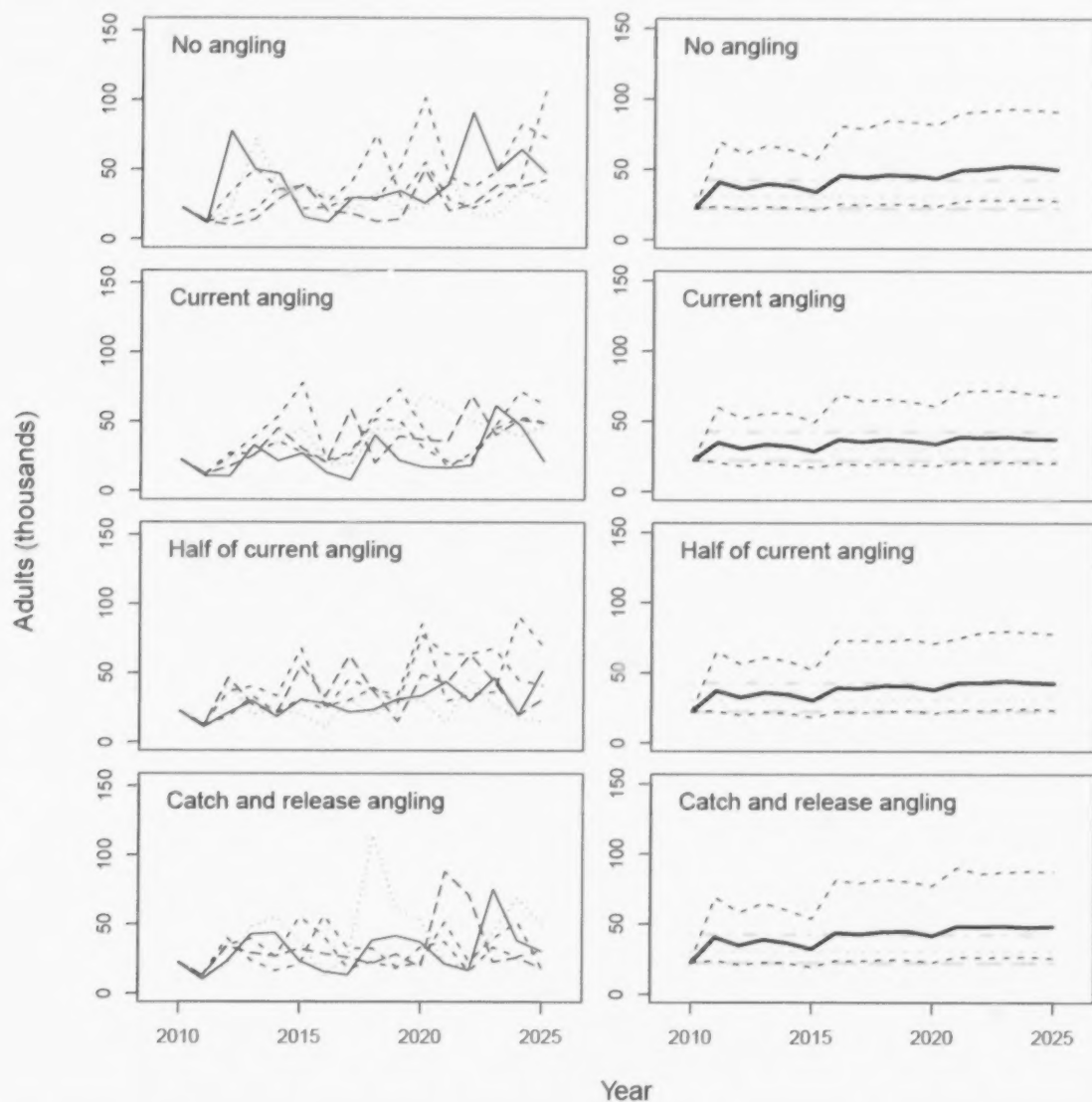


Figure 9. Population projections for DU 4 Atlantic Salmon using the combined Beverton-Holt and Ricker models for freshwater production and an average marine survival of 5%. Plots on the left represent 5 randomly selected projections from a total of 1000 simulations. Plots on the right show median values from 1000 simulations per year. Dashed black lines represent 10th and 90th percentiles of the data. Grey lines represent population abundances levels for current abundance (dashed line), conservation requirement/recovery target (dotted line) and pre-decline mean (dash-dot-dash line).

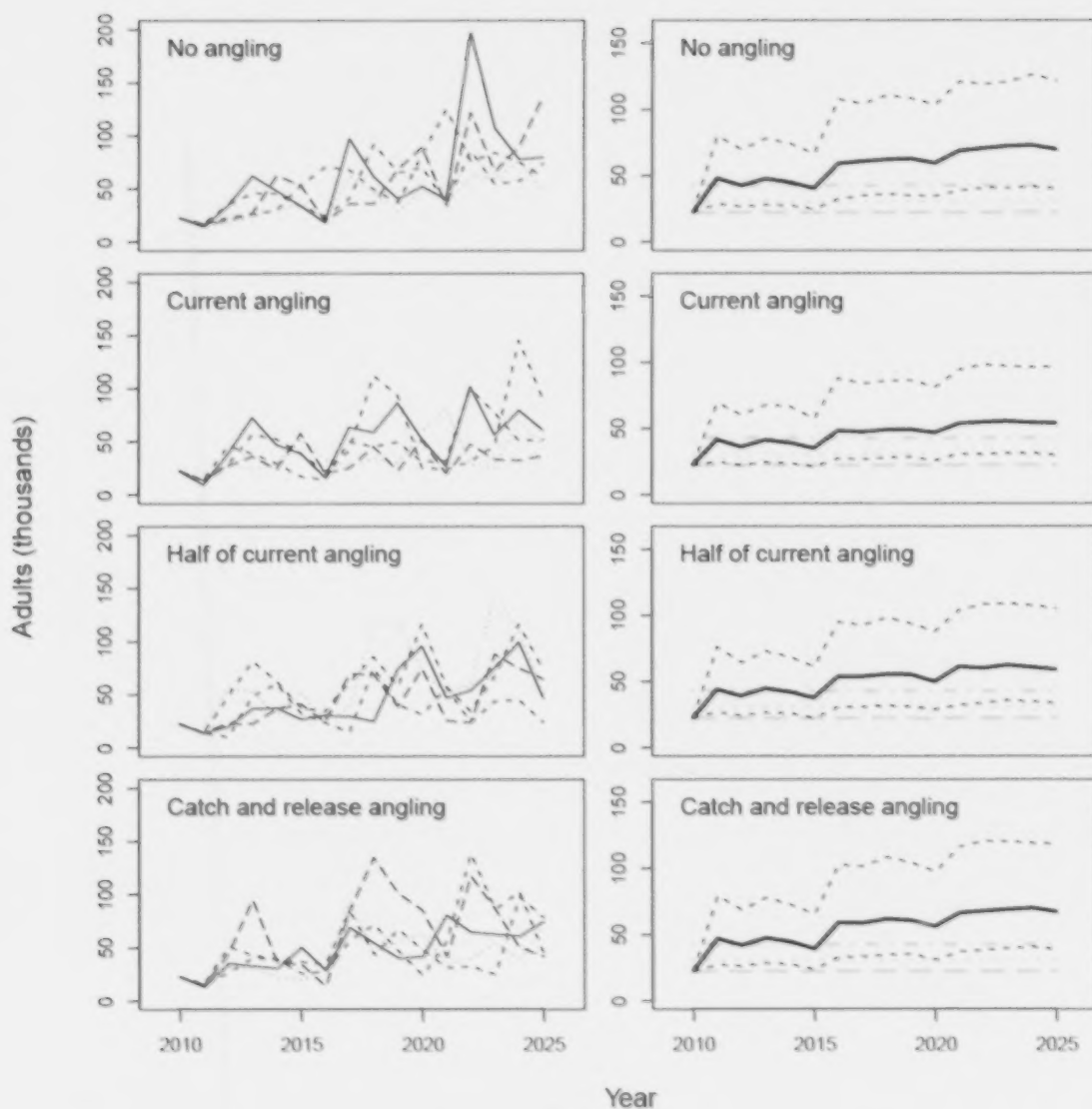


Figure 10. Population projections for DU 4 Atlantic Salmon using the combined Beverton-Holt and Ricker models for freshwater production and an average marine survival of 6%. Plots on the left represent 5 randomly selected projections from a total of 1000 simulations. Plots on the right show median values from 1000 simulations per year. Dashed black lines represent 10th and 90th percentiles of the data. Grey lines represent population abundances levels for current abundance (dashed line), conservation requirement/recovery target (dotted line) and pre-decline mean (dash-dot-dash line).

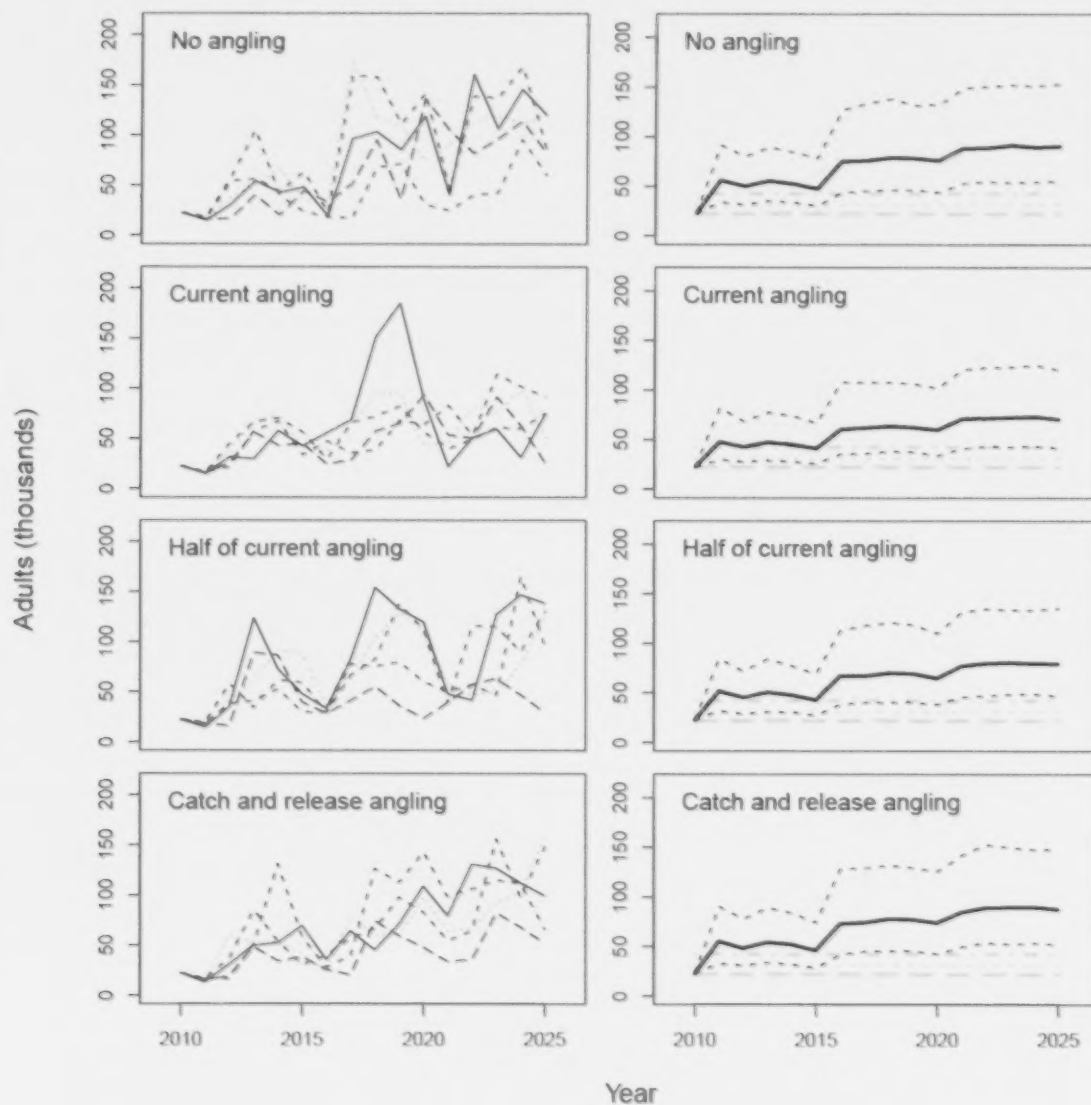


Figure 11. Population projections for DU 4 Atlantic Salmon using the combined Beverton-Holt and Ricker models for freshwater production and an average marine survival of 7%. Plots on the left represent 5 randomly selected projections from a total of 1000 simulations. Plots on the right show median values from 1000 simulations per year. Dashed black lines represent 10th and 90th percentiles of the data. Grey lines represent population abundances levels for current abundance (dashed line), conservation requirement/recovery target (dotted line) and pre-decline mean (dash-dot-dash line).

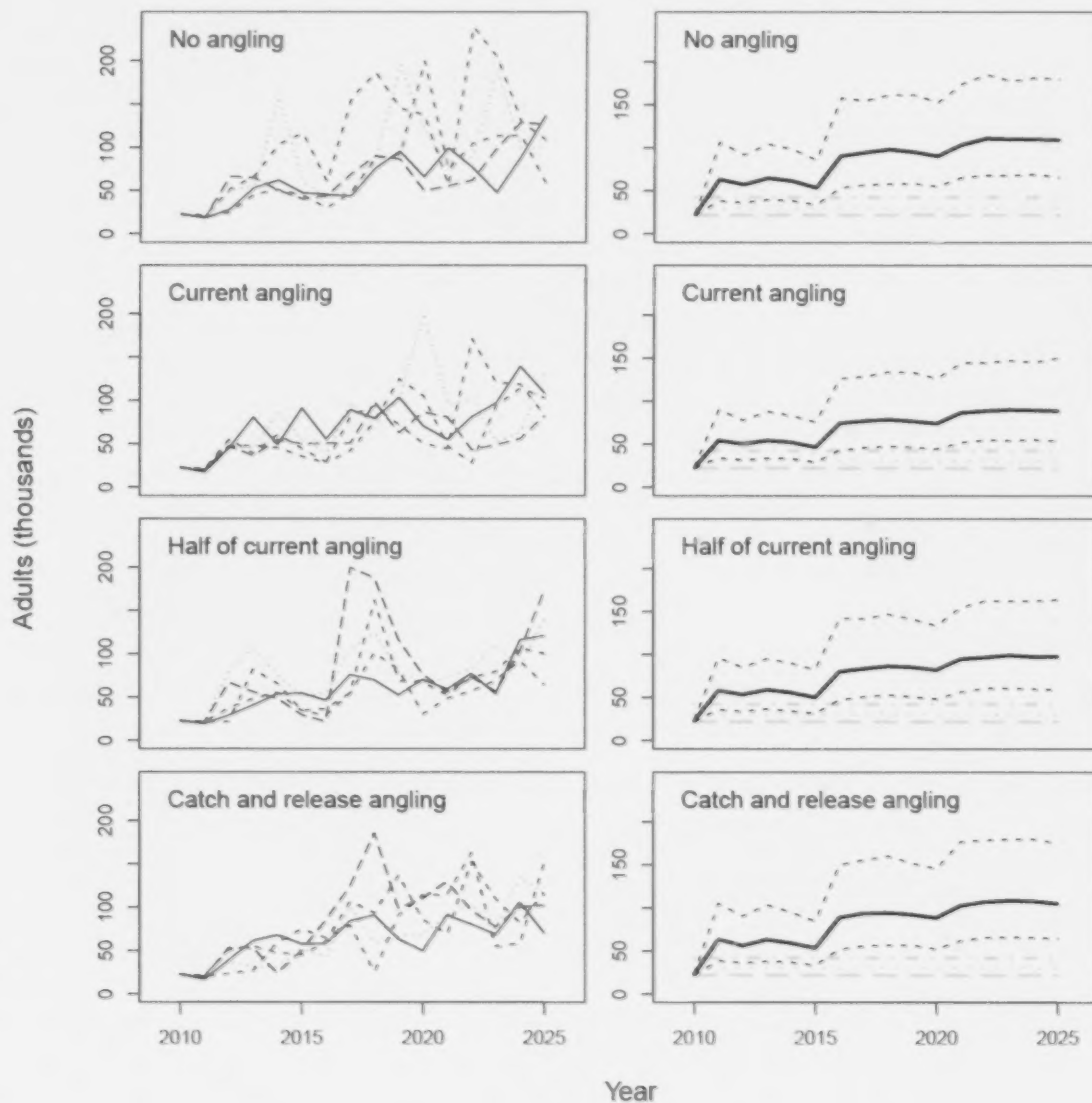


Figure 12. Population projections for DU 4 Atlantic Salmon using the combined Beverton-Holt and Ricker models for freshwater production and an average marine survival of 8%. Plots on the left represent 5 randomly selected projections from a total of 1000 simulations. Plots on the right show median values from 1000 simulations per year. Dashed black lines represent 10th and 90th percentiles of the data. Grey lines represent population abundances levels for current abundance (dashed line), conservation requirement/recovery target (dotted line) and pre-decline mean (dash-dot-dash line).

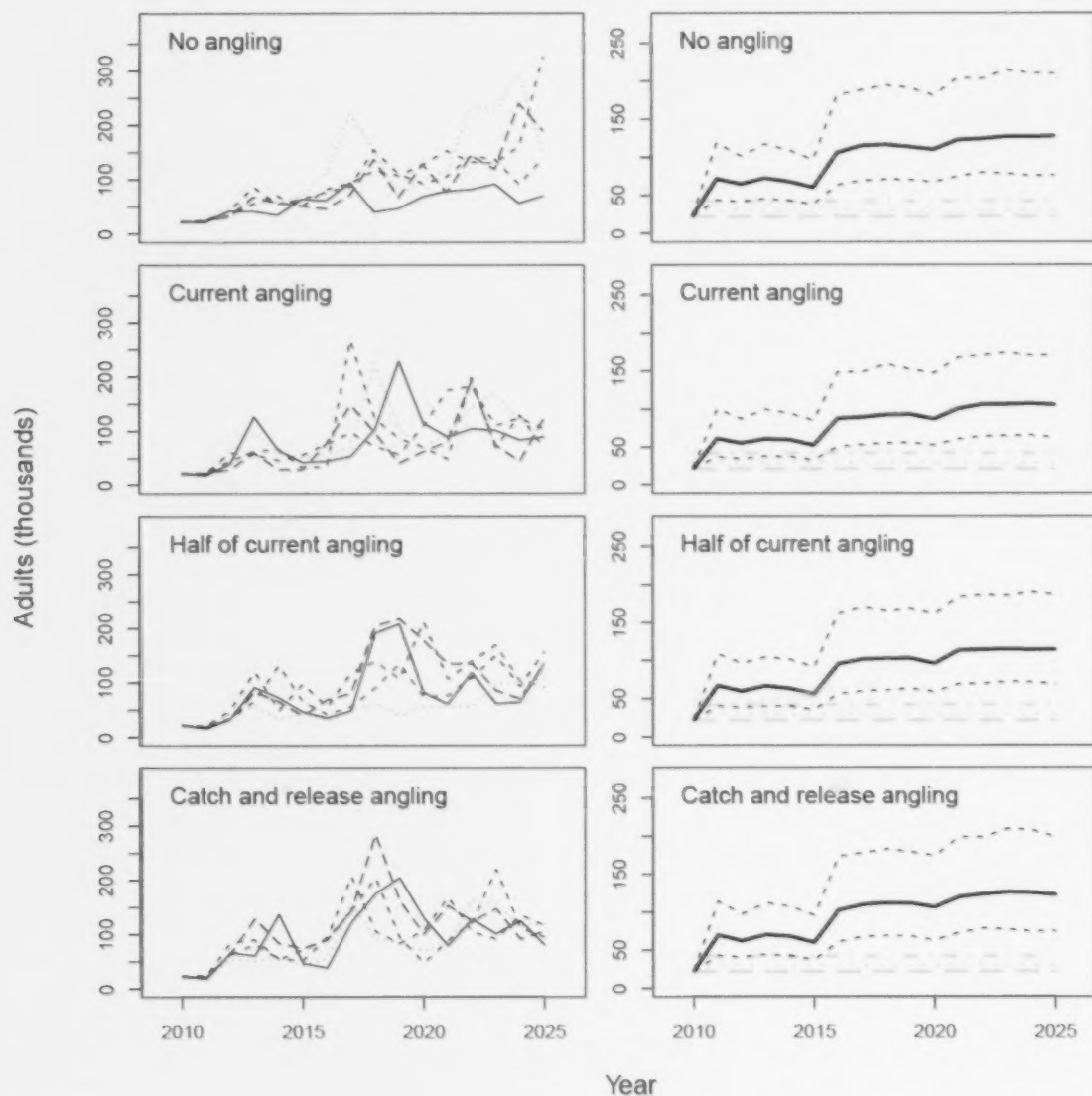


Figure 13. Population projections for DU 4 Atlantic Salmon using the combined Beverton-Holt and Ricker models for freshwater production and an average marine survival of 9%. Plots on the left represent 5 randomly selected projections from a total of 1000 simulations. Plots on the right show median values from 1000 simulations per year. Dashed black lines represent 10th and 90th percentiles of the data. Grey lines represent population abundances levels for current abundance (dashed line), conservation requirement/recovery target (dotted line) and pre-decline mean (dash-dot-dash line).